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TELEPHONE LINE TRANSMISSION OF TELEMETRY DATA

J. C. Hansen

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INTRODUCTION

Early in the ground-range planning for Project Mercury, there existed a requirement for the transmission of telemetered data in real time from certain of the sites to the Control Center at Cape Canaveral via leased telephone facilities. Sites were included in the plan which had land line communications facilities to the Control Center. Since this requirement imposed leasing additional voice frequency facilities, it was later deleted as an economy measure. However, the Laboratory had been requested to evaluate a method of transmission for this data and since a considerable sum of money had been invested in test equipment plus the interest the results might have for future projects, it was decided to conduct the experiment on a part time basis. The basic requirement was to provide a central location with a substantial sample of data telemetered from the capsule. By this means, deviations of critical quantities could be detected earlier by the establishment of data trends covering a number of sites. This information, transmitted in real time, would enable the central location to exert the maximum degree of mission control in terms of early detection of abnormalities, and the issuance of proper corrective procedures to the remote site in question. Another advantage of this system, other than centralized control, was the opportunity of placing a few highly trained and competent personnel (e.g., Flight Surgeon, Capsule Environment Observer, etc.) in one location for data interpretation. The requirement is still existent and is satisfied by teletype or voice communication of telemetry summaries in non-real time. The system degradations that ensue are delay and loss of control.

The experiment description that follows is a specialized one in that it applies for a specific Mercury task. However, the method is applicable in general to other users of Inter-Range Instrumentation Group (IRIG) standards.

I. Data Requirement

The information to be transmitted in real time involved three continuous channels of analog data and one channel of selected sampled analog and event data. These data are transmitted from the capsule via IRIG channels Nos. 5, 6, 7 and 12. The description of the data and their frequency responses are illustrated in Figure 1. The EKG No. 1, No. 2, and Respiration are the three continuous analog quantities. The remainder of the quantities are sampled data.

Since land line transmission of the above data would involve at least the voice frequency bandwidth, it was decided to appropriately frequency multiplex, in one voice frequency circuit, in the following manner. (Ref. 1)

	IRIG Channel	Frequency Response * (CPS)	Center Frequency (CPS)
Respiration	3	11	760
Sampled Events	4	14	960
EKG No. 1	5	20	1300

* Based on a modulation index = 5

EKG No. 2	6	25	1700
Sampled Analog	7	35	2300

The frequency division was made in this manner because of equipment availability for the standard IRIG channels. In order to lower the sampling rate for channel No. 7, the sixteen "event" quantities were separated from the "analog" quantities and transmitted over channel No. 4. This resulted in better bandwidth utilization and since no pulse height measurements of the "events" data is necessary, the restricted bandwidth offers no difficulty. The respiration channel frequency response of 11 cps is adequate since rate and depth of the transmitted waveform are the parameters of interest. There was some question as to the frequency response needed for the EKG waveform so that an experiment was performed transmitting EKG over narrow bandwidth channels. (Ref. 2) Results of this test indicated a 20 cps response as adequate for medical interpretation for this mission.

II Test Description

1. Sources of Data

a. Respiration

This input was simulated with a 10 cps sine wave.

b. EKG Nos. 1 and 2

An electrocardiograph was used to make a magnetic tape recording and an electrocardiogram simultaneously. The magnetic tape was then used as an input for EKG Nos. 1 and 2.

c. Sampled Data

Since it was required to transmit 15 analog quantities plus 16 event quantities, a two-pole 20 x 1 commutator was wired as follows:

Pole No. 1	15 analog positions
	2 reference (0 and 100) positions
	2 master pulse positions
Pole No. 2	16 event quantities positions
	2 master pulse positions

As a 20 x 1 commutator was not available commercially, a 30 x 1 commutator was modified to operate at a 30 x 2/3 rate which resulted in an equivalent pulse rate of 20 cps. A staircase pattern was generated as the analog quantities input and an alternating 0-5 volt pattern was used for the events.

2. Test Arrangement

Figure 2 illustrates in block diagram form the experimental setup. Channels 3, 4, 5, and 6 operated at 7.5 per cent deviation, modulation index = 5. Channel 7 operated at 7.5 per cent deviation, modulation index = 1.5. Linear phase band pass and low pass filters were used on Channel 7.

A commercially available decommutator, modified to operate at 20 cps, was used on Channel 7. The sync and timing pulses from this decommutator triggered a laboratory-built device for decommutating and displaying the 16 events.

Four different leased telephone facilities were employed in a loop arrangement as follows:

(a)	H-44 cable	337 miles
(b)	TD-2 (L-carrier)	697 miles
(c)	L-carrier	1344 miles
(d)	K-carrier	824 miles

These circuits were ordered as "voice" circuits with no special engineering or monitoring other than standard company practice. Since there is no "standard" voice facility, these results should be considered sampling of behaviour on this type of facility.

III Test Results

1. EKG No. 1 and No. 2

Figure 3 illustrates an electrocardiogram recorded of a patient resting in a supine position. This is a technically well recorded electrocardiogram as defined by a steady base line and absence of AC interference and tremor. The leads are identified as I, II and III. I (the potential difference measured between the left and right arms) was transmitted over both Channels 5 and 6. The frequency response of the recorder is 100 cps. Figure 4 shows EKG No. 1 and No. 2 as recorded after transversing 1344 miles of L-carrier over IRIG channels 5 and 6. The P, QRS and T structure of the waveform (Ref. 3) is reproduced accurately although EKG 1 and 2 shown are restricted to bandwidths of 20 and 25 cps respectively.

Figure 5 shows another electrocardiogram before and after transmission over the same loop. This recording was made under identical conditions on a different patient with a diagnosed heart abnormality.

The top recording is the original and one can note the tremor along the base line which is subsequently filtered out during the transmission process. This is actually no disadvantage as tremor is usually caused by a tense patient and has no diagnostic significance. One also notes that the QRS complex is biphasic and may be associated with right ventricular enlargement. There is also a very evident atrial premature beat which has little clinical significance but illustrates the case of recognition of this rhythmical disorder after transmission. It appears that evident abnormalities in the complex waveform can be transmitted over long distances without appreciable distortion.

The conclusion here is that both respiration and EKG waveforms may be transmitted quite successfully by this method. Impulsive noise and cross-talk as commonly encountered on telephone circuits are not serious problems as regards transmission of the above types since the waveforms are repetitive and short duration distortions are quite easily recognized as being due to the communications facility. The general paroxysmal conditions of the heart last on the order of a few minutes to a few hours and could not be mistaken for transient noise. The one exception to the above is a "startle pattern" (Ref. 4) which closely resembles a noise burst. This pattern was obtained by firing a pistol shot near a patient.

An attempt was made to duplicate this experiment but the resulting pattern was impossible to interpret as due to heart action or patient movement.

2. Events

Figure 6(a) shows the commutator output representing a sequence of event quantities (i.e., either on or off). These data were sent over IRIG Channel 4. The received waveform before decommutation is shown in Figure 6(b). The distortion due to narrow band transmission is evident but since one is interested only in an adequate level change for slicing, the waveform is satisfactory. Figure 10 is a block diagram of decommutator No. 2 which was engineered for this experiment by R. Greim of Group 25. The unit uses the synch and timing pulses from the commercial decommutator. A simple parity check error counter was added in order to measure the number of bits in error. No attempt was made to measure transpositions of bits in a frame or error distributions as the data for events are repeated every second resulting in self-correction. The results indicated an error count averaging 1 in 10^4 bits over the four facilities used for a cumulative period of 100 hours.

This method of transmitting event data is satisfactory whenever there is sufficient bandwidth for adjacent pulse resolution (see Appendix).

3. Sampled Analog Data

The staircase pattern shown in Figure 6(c) was used as the sampled analog input. As the analog quantities are slowly varying ($f < 0.5$ cps), a sampling frequency of $F = 1$ cps is adequate. The pulse rate of 20 cps was used with a linear phase low pass output filter with a response to 110 cps (see Figure 6(d)). Various response low pass filters were tried from 35 to 300 cps in order to obtain a balance between signal-to-noise ratio and adjacent channel cross-talk. The situation is different from that of the events data in that the height of each pulse is measured. The objective was to attain an accuracy of 2 per cent for overall transmission from the capsule to the remote control center.

Since various factors operated to reduce the transmission accuracy, the test was conducted in several phases as follows:

(a) Calibration

(b) Back-to-back, Channel 7 only

(c) Back-to-back, All channels

(d) Via telephone line loop, Channel 7 only

(e) Via telephone line loop, All channels

(a) Calibration

This test was performed in order to insure that the decommutator gates were operating properly. The decommutator used has a normal operating range of 75-900 pps and had to be modified to operate at the lower rate of 20 pps. Figure 7(a) shows the output of one gate when the decommutator is operating on internally generated calibration pulses. The height of the pulses was 27 volts and the oscilloscope sensitivity was 1 volt per cm.

(b) Back-to-Back, Channel 7 only (Figure 7b)

This test used the commutator-multiplexer-discriminator decommutator combination. The measured accuracy was approximately 0.4 per cent. Most of this error was due to the decommutator attempting to handle the low pulse rate input for which it was not designed. The information pulses fed to the output gates were not flat topped but rather sloped off some 10 per cent. This was due mainly to the first re-cycle detector which is a peak detector for the information pulses. The circuit would not hold for the entire pulse length but would leak. This meant that any jitter in the output gate timing trigger would result in a pulse height measurement at a different point on the sloped top. This 0.4 per cent error is discounted since decommutators are available which will operate down to 10 pps.

(c) Back-to-Back, All Channels

Figures (7c) and (7d) show the gate output and the information pulse train detail. The maximum pulse amplitude of the pulse train shown is 5 volts. The slight decrease in accuracy is due to cross-talk from the other subcarrier frequencies (see Appendix). It arises from non-linearity in either the multiplexer amplifier or the discriminator input circuit or both.

(d) Via Telephone Line Loop

This test was run over four different facilities whose characteristics are shown in the Appendix.

(i) H-44 cable, Channel 7 only

Figures 7(e) and 7(f) show the response for this facility. It is seen that the accuracy is still well under 1 per cent for the transmission of Channel 7 data only.

(ii) H-44 cable, All Channels

Figures 8(a) and 8(b) show the results for five-channel transmission over H-44 cable. It is evident that cross-talk frequencies are being generated by non-linearities along the circuit. Since these circuits received no special attention, it is probable that one or more repeater amplifiers are providing a non-linear response. The transmission accuracy has decreased to approximately 1.2 per cent.

(iii) K-carrier, Channel 7 only

Figure 8(c) shows the gate output for transmission over the K-carrier facility. Despite the absence of the other subcarrier frequencies, there is cross-talk being generated on the facility. As this occurs to some degree on all the carrier system facilities but is absent on the H-44 cable for one channel transmission, it indicates the presence of interfering frequencies on these channels.

(iv) K-carrier, All Channels

Figures 8(d) and 8(e) illustrate typical results for K-carrier transmission of all channels. It is noted that there is little difference between the transmission of one or five channels as regards the cross-talk level. The accuracy of the gate output is 1.5 per cent.

(v) TD-2 (L-carrier)

Figures 9(a), 9(b) and 9(c) show the results for TD-2 transmission of one and five channels. The results are exactly the same as for K-carrier above.

(vi) L-carrier, Channel 7 only

This circuit loop of 1340 miles is most typical with regard to distance of transmission, as most of the Mercury circuits required would average 1000 miles or more. Figure 9(d) shows a rather violent dispersion of gate level output resulting in an accuracy of about 7.3 per cent. This result varied considerably depending upon the period measured. A monitor of the circuit showed varying levels of interference which appeared to be cross-talking voice conversations (see Figures 6(e) and 6(f)).

(vii) L-carrier, All Channels

This mode of transmission was uniformly inaccurate due to the level of cross-talk from the other four sub-carrier frequencies. Figures 9(e) and 9(f) illustrate the results.

(viii) Evaluation

The transmission of sampled analog data via "voice" circuit facilities with the desired degree of accuracy (~1 per cent) does not appear feasible by the method here described. The accuracy could be improved to approach 1 per cent by using a separate facility for the sampled data in order to avoid the other frequencies and by a constant monitoring and adjustment of the used facility. Unfortunately, one has also to control the other circuits sharing a common carrier in the same manner which makes a very difficult arrangement. It is not a question of engineering the circuit to specified tolerances as regards delay and overall amplitude as neither of these is a factor. It is a combination of interfering voice band frequencies which may arise from a number of sources plus a degree on non-linearity in the facility. There is a continuing task of cross-talk suppression and circuit gain adjustment in progress at all times by the telephone company. Such adjustment is usually limited to occasions of customer complaint since it is impossible to monitor all circuits at all times.

These tests suggest that a more practical and profitable means of transmitting sampled data should be by digital methods where a degree of accuracy consistent with the vehicle to ground path is attainable.

Appendix I

Cross-Talk

Interference of this type is here defined by the input-output relation.

$$(1) \qquad e_o = a_1 e_i + a_2 e_i^2 + a_3 e_i^3 + \ldots$$

where e_o is the output corresponding to an input of e_i. If the input consists of a number of subcarriers of frequencies $\omega_1 \ldots \omega_n$, then the input expression becomes:

$$(2) \qquad e_1 = \cos \omega_1 t + \cos \omega_2 t + \ldots \cos \omega_n t$$

If one now substitutes (2) in (1) and employs suitable arithmetic, a number of cross modulation frequencies appear.[5] For the five channels used in this experiment, the following cross modulation frequencies were found to be within the pass band of the input filter of Channel 7 at 2300 cps center frequency.

$f_2 + f_3 = 2260$ cps

$f_3 + f_4 - f_1 = 2270$

$f_1 + f_4 = 2430$

$3f_1 = 2190$

$2f_1 + f_2 = 2420$

where:

$f_1 = 730$ cps

$f_2 = 960$

$f_3 = 1300$

$f_4 = 1700$

$f_5 = 2300$

Appendix II

Pulse Resolution [6]

The standard response of a low pass filter with constant atten-uation k and linear phase $\Delta\phi = -g\omega$; i.e.,

$$G(t) = \frac{k}{\Pi}\{Si[\omega_s(t-g-T_1)] - Si[\omega_s(t-g-T_2)]\}$$

ω_s = cutoff frequency

T_1 = Leading edge

T_2 = Trailing edge

g = Constant

Using superposition one can apply this result to two adjacent pulses and add the responses; i.e.,

$$G(t) = \frac{k}{\Pi}\{Si[\omega_s(t-g-T_1)] - Si[\omega_s(t-g-T_2)]$$

$$+ Si[\omega_s(t-g-T_3)] - Si[\omega_s(t-g-T_4)]\}$$

A plot of the above shows that sufficient resolution for pulse identification occurs for

$$f_s = \frac{\omega_s}{2\,\Pi} = \frac{1}{2(T_2 - T_1)}$$

Appendix III

Equipment and Facilities

1	Sanborn Model 154-100B 4-channel recorder
4	Sanborn Model 150-1600 ECG pre-amplifiers
4	Sanborn Model 150-200 B/400 driver amplifiers
5	Geotech Model 450 voltage controlled oscillators
1	Geotech Model 3515 multiplexer
4	Geotech Model 4610A Subcarrier Discriminators
1	Data-Control Model GFD-2 Subcarrier Discriminator
1	Ampex Model FR-100A Recorder
1	K-carrier loop circuit number FD1324
1	L-carrier loop circuit number FD2423A
1	TD-2 loop circuit number FD11976
1	H-44 cable circuit number FD1538
1	General Devices 2 pole 30 x 1 commutator
1	Arnoux Model TD5 Decommutator

Figures 11 through 18 show the line characteristics of the facilities used.

References

1. "Real Time Telemetry Transmission," J. C. Hansen, Mercury Memorandum 20-0009, 26 August 1959

2. "Transmission of Electrocardiograms," J. C. Hansen, Mercury Memorandum 20-0029, 19 February 1960

3. IBID 2

4. "Electrocardiography in Practice," Graybiel et al, Saunders, 1952, p 71.

5. "Radio Telemetry," Nichols and Rauch, Wiley 1957, p 79.

6. "Frequency Analysis Modulation and Noise," Goldman, McGraw-Hill, 1948, p 85.

Quantity	Frequency Response	Range of Measurement	Manner of Display
EKG # 1	20 cps		
EKG # 2	20 cps		
Respiration R and D	10 cps		
Body Temperature	.5 cps	90° to 105° F	Meter
Suit Inlet Air Temperature	.5 cps	40° to 100° F	Meter
O_2 Partial Pressure	.5 cps	0-253 mm Hg	Meter
O_2 Supply Pressure	.5 cps	0-7500 PSIA	Meter
O_2 Emergency Supply Pressure	.5 cps	0-7500 PSIA	Meter
Suit Pressure	.5 cps	0-25 PSIA	Meter
CO_2 Partial Pressure	.5 cps	0.1 - 51.7 mmHg	Meter
Cabin Pressure	.5 cps	0-25 PSIA	Meter
Cabin Air Temperature	.5 cps	0 to 200° F	Meter
Acceleration Nz	.5 cps	+ 30 G	Meter Strip Chart
Attitude Pitch	.5 cps	$\overline{0}$ - 320°	Meter Strip Chart
Attitude Roll	.5 cps	0-320°	Meter Strip Chart
Attitude YAW	.5 cps	0-320°	Meter Strip Chart
DC Supply Voltage	.5 cps	0 to 30 VDC	Meter
AC Supply Voltage	.5 cps	0 to 120 VAC	Meter
Abort. Initiate	On-Off Event		Lamps
AC Power Failure	On-Off Event		Lamps
DC Power Failure	On-Off Event		Lamps
Alarm	On-Off Event		Lamps
Retro Angle Command	On-Off Event		Lamps
Retro Rocket # 1 Fire	On-Off Event		Lamps
Retro Rocket # 2 Fire	On-Off Event		Lamps
Retro Rocket # 3 Fire	On-Off Event		Lamps
Retro Rocket Jett	On-Off Event		Lamps
Ant. Firing Release	On-Off Event		Lamps
Pilot Chute Deploy	On-Off Event		Lamps
Drough Chute Deploy	On-Off Event		Lamps
Main Chute Deploy	On-Off Event		Lamps
Capsule Ring Separate	On-Off Event		Lamps
Rescue Aids	On-Off Event		Lamps
Main Chute Jett	On-Off Event		Lamps

Table of Telemetered Quantities

Figure 1

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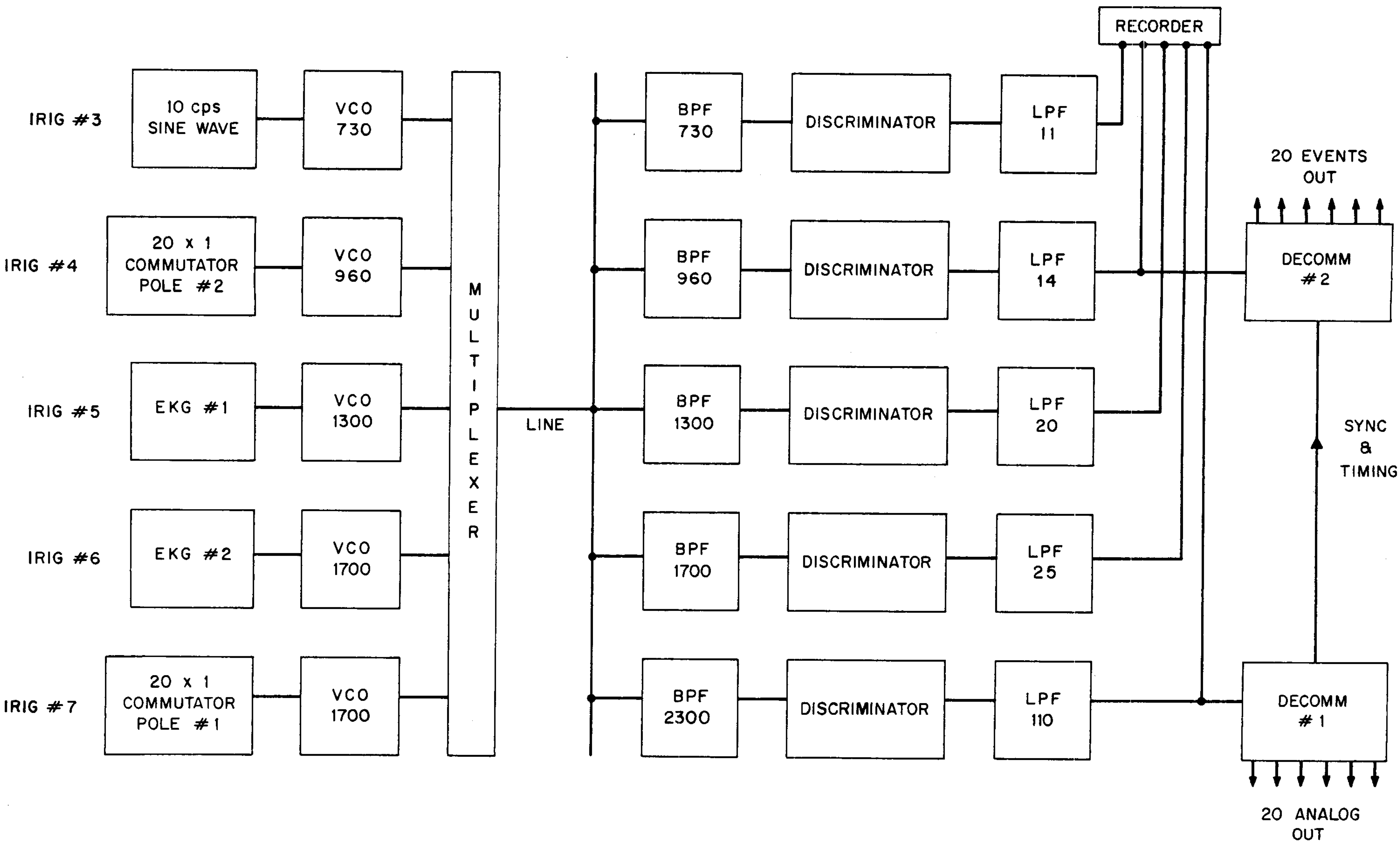
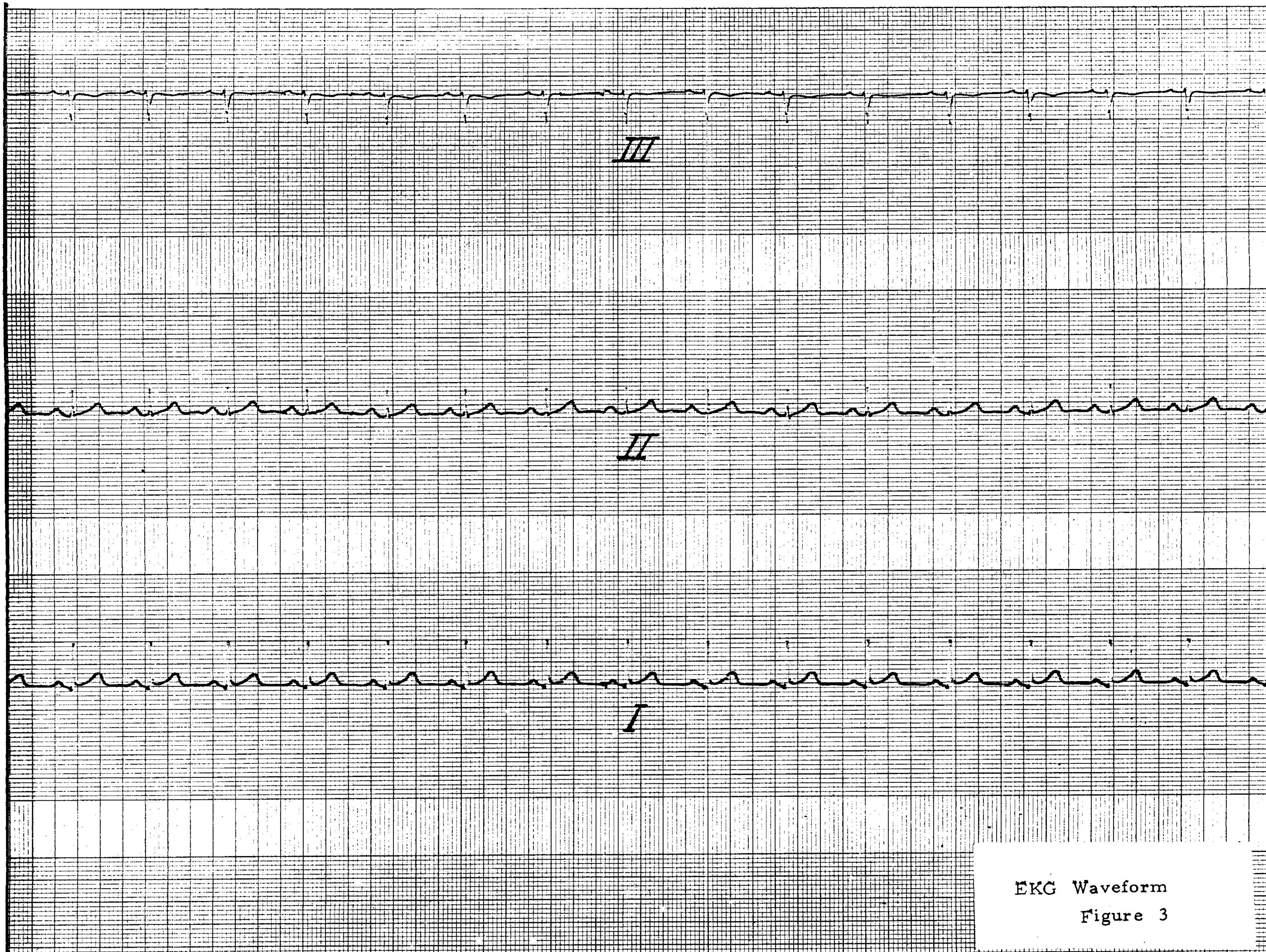
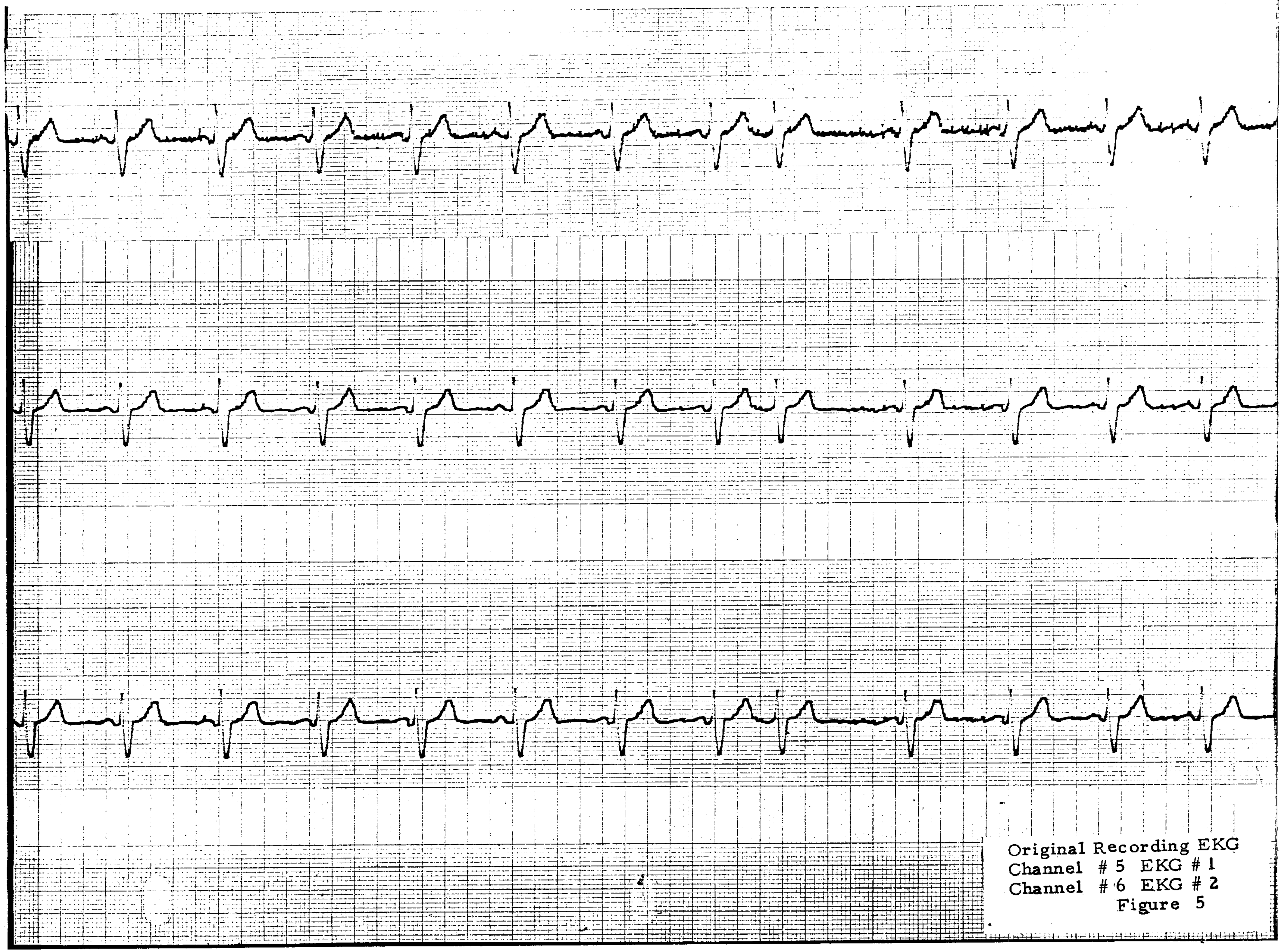


FIG. 2 EXPERIMENTAL TEST ARRANGEMENT

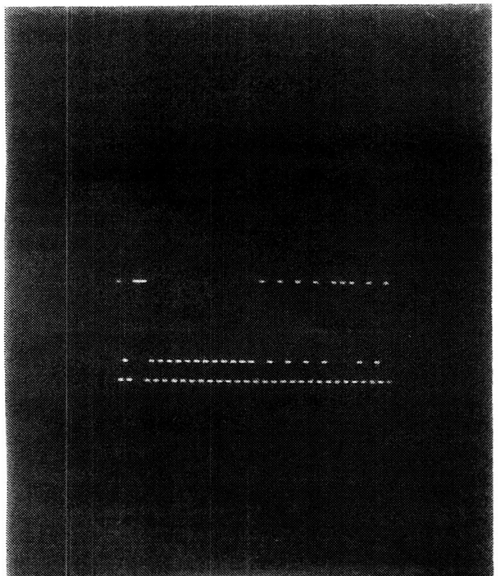


EKG Waveform
Figure 3

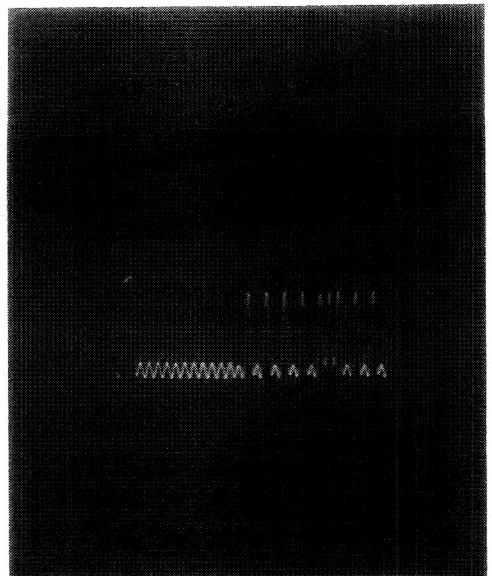
Figure 4



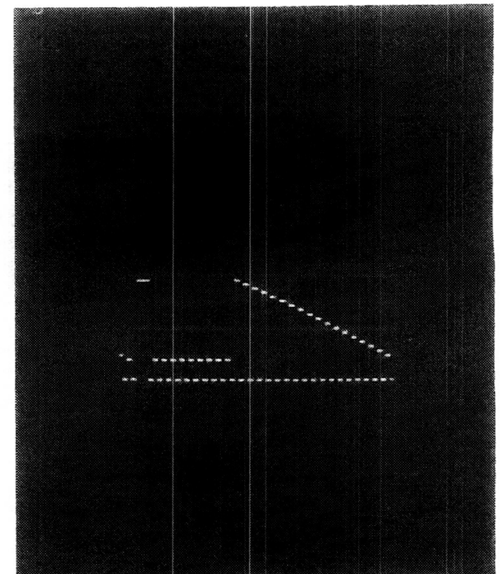
Original Recording EKG
Channel # 5 EKG # 1
Channel # 6 EKG # 2
Figure 5



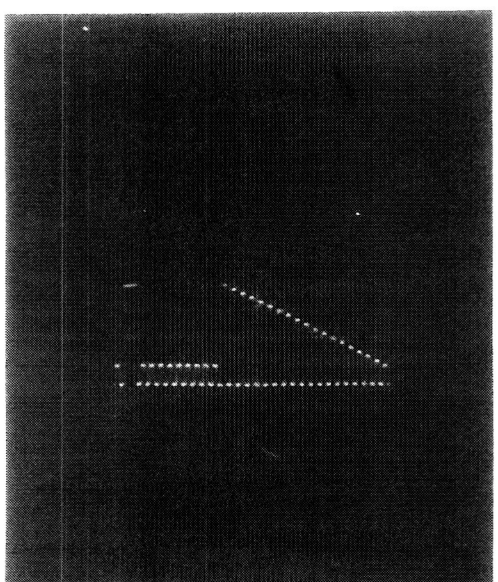
Commutator Output
Figure 6(a)



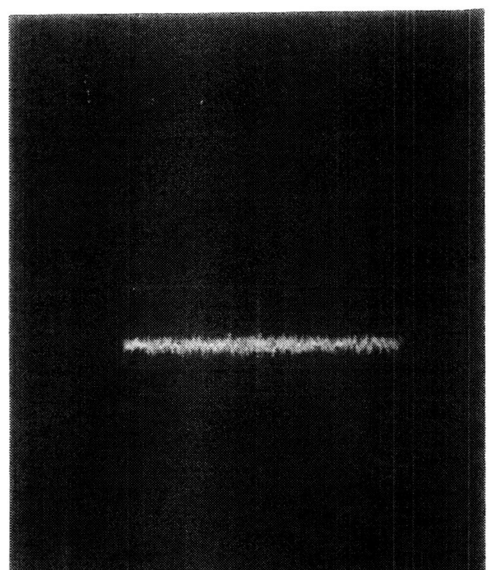
Commutator Output
Figure 6(b)



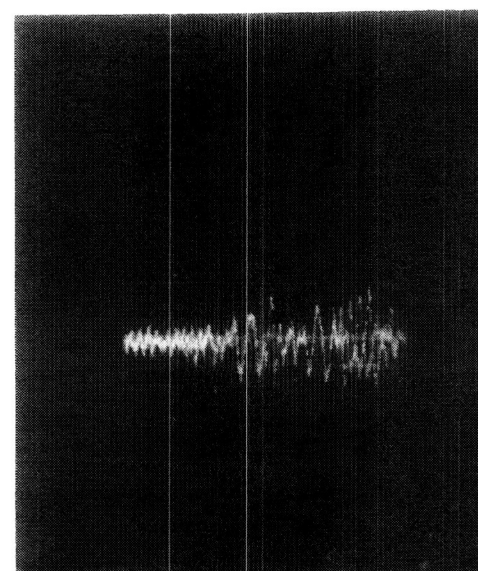
Commutator Output
Figure 6(c)



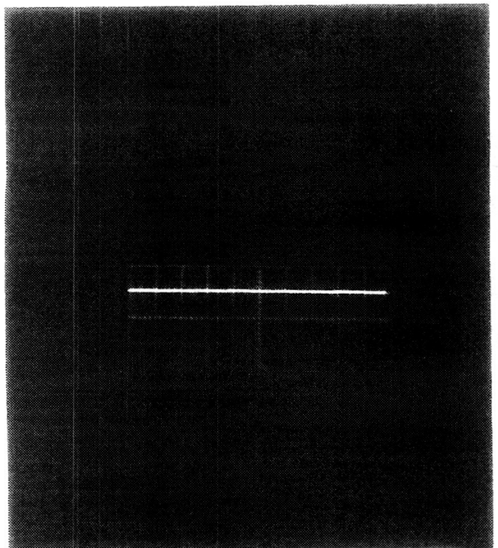
Discriminator Output
Figure 6(d)



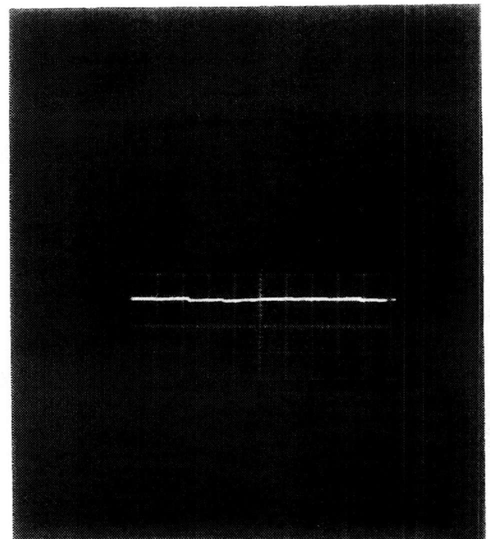
Line Noise~ 30 db
Figure 6(e)



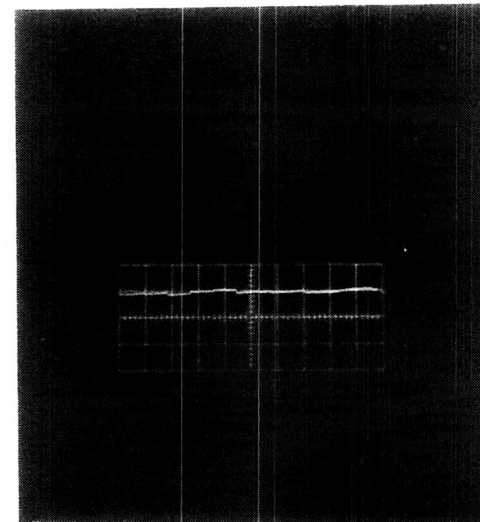
Cross Talk
Figure 6(f)



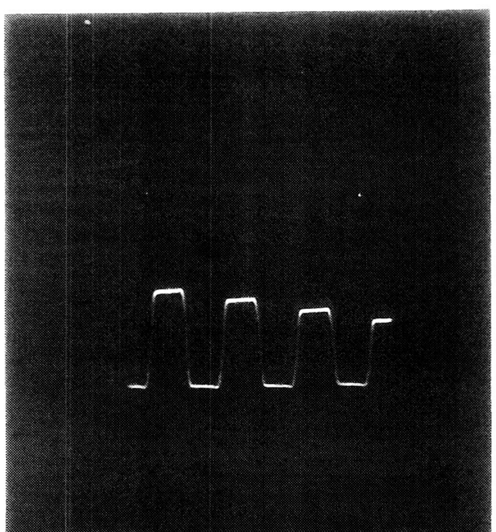
Calibration
Figure 7(a)



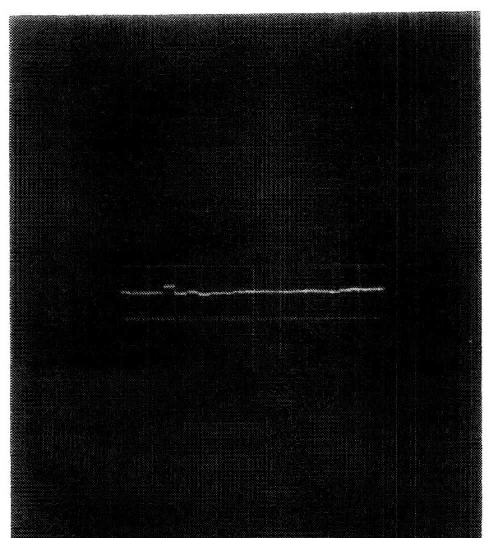
Back-to-Back
Channel 7 only
Figure 7(b)



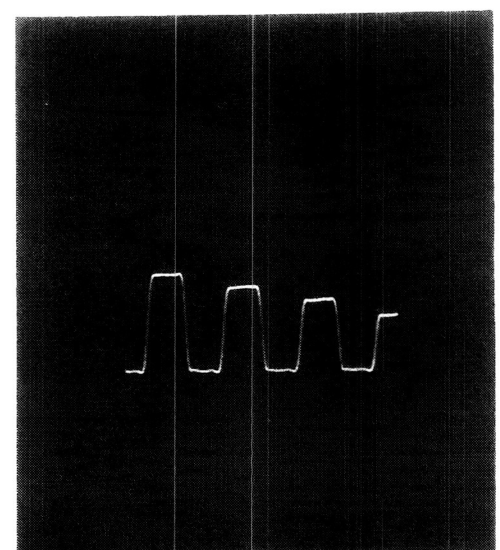
Back-to-Back
All Channels
Figure 7(c)



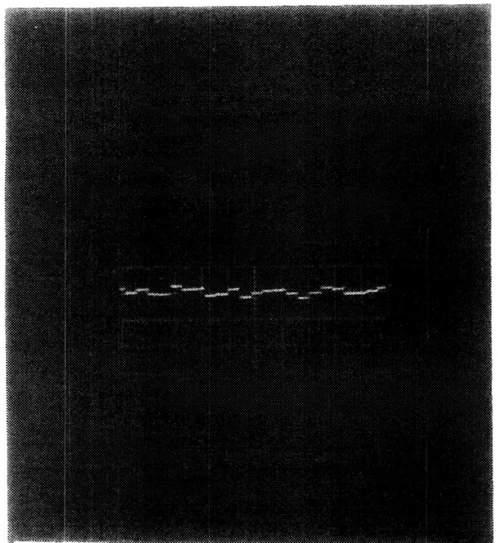
Back-to-Back
All Channels
Figure 7 (d)



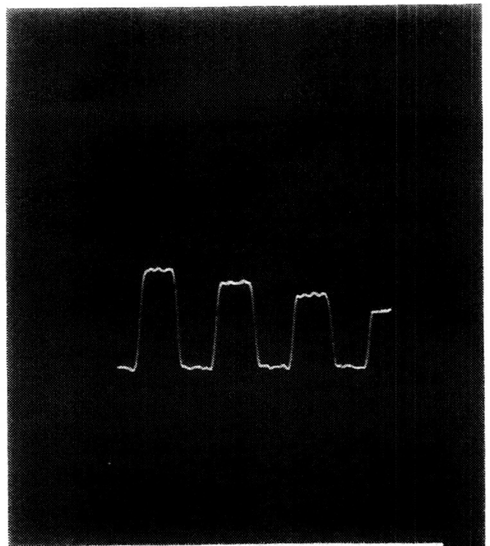
H-44
Channel 7 only
Figure 7(e)



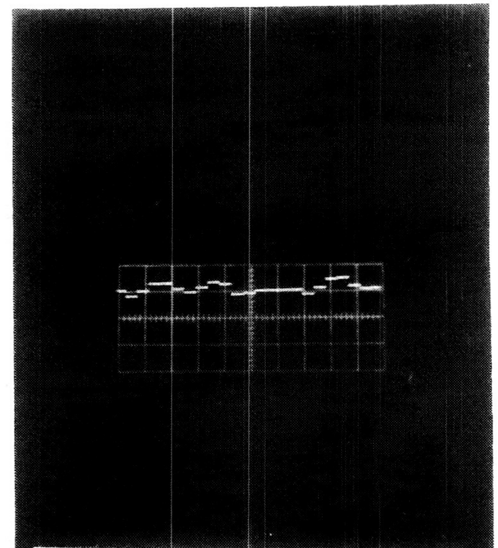
H-44 Channel 7 only
Figure 7(f)



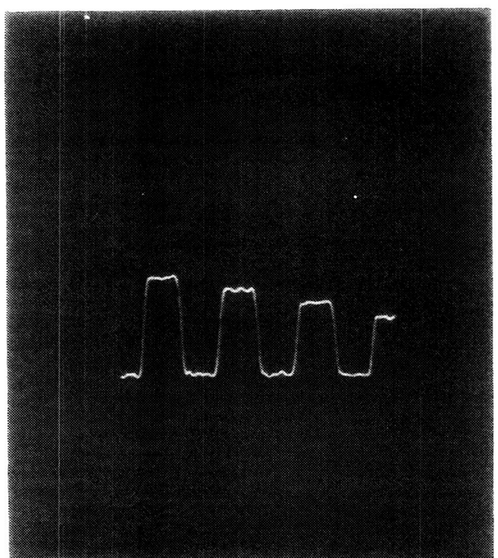
H-44 All Channels
Figure 8(a)



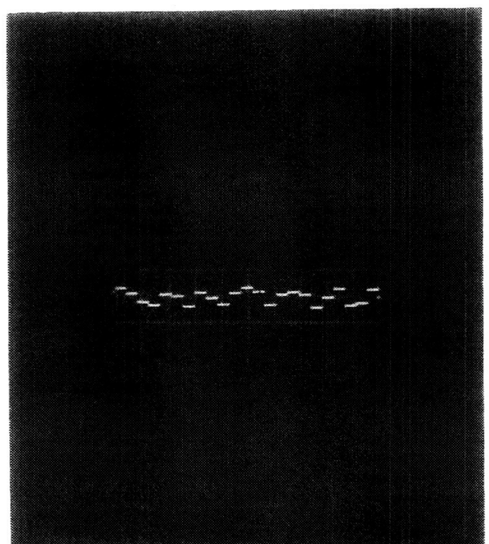
H-44 All Channels
Figure 8(b)



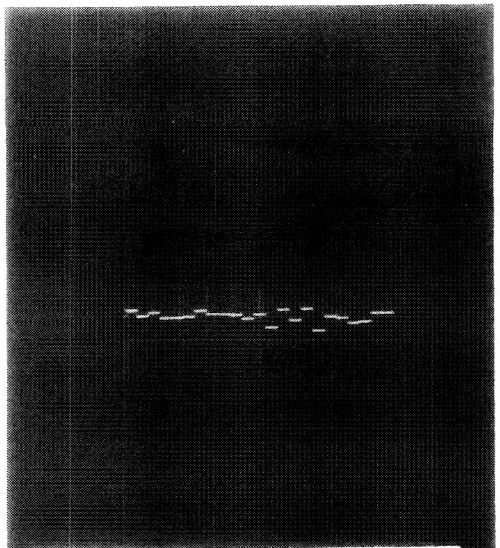
K-carrier Channel 7
Figure 8(c)



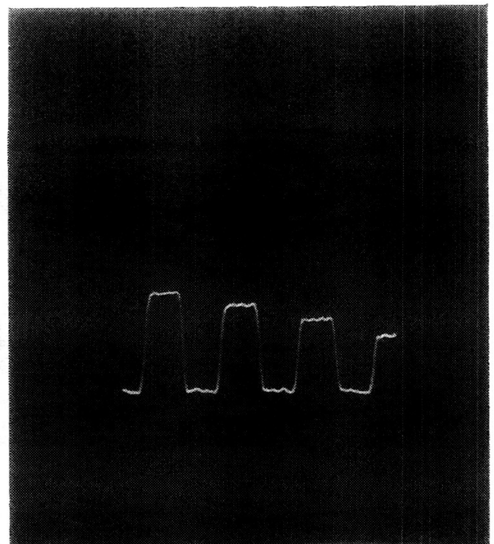
K-carrier All Channels
Figure 8(d)



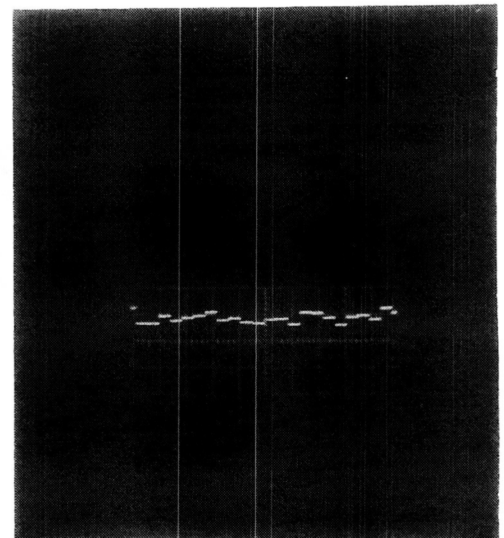
K-carrier All Channels
Figure 8(e)



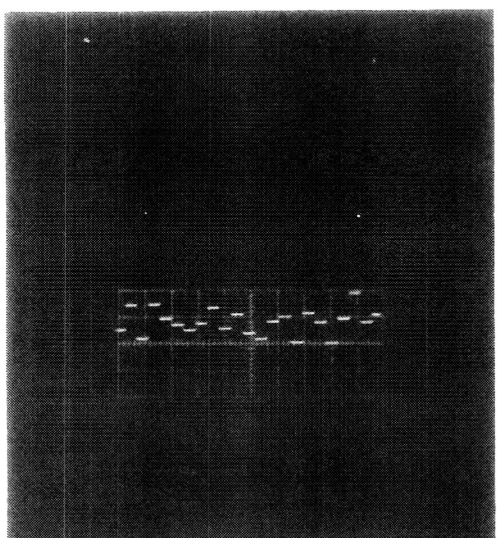
TD-2 (L carrier)
Channel 7 only
Figure 9(a)



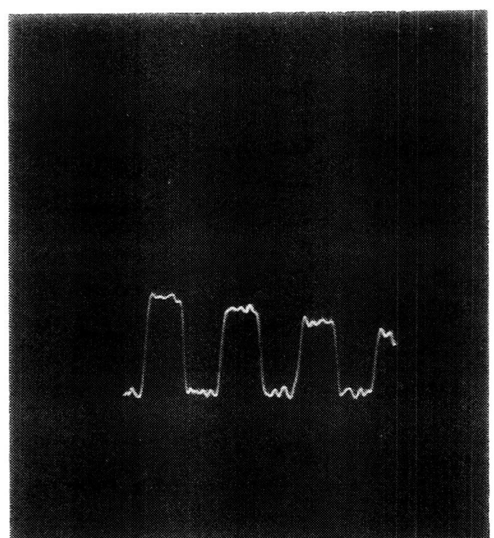
TD-2 (L carrier)
All Channels
Figure 9(b)



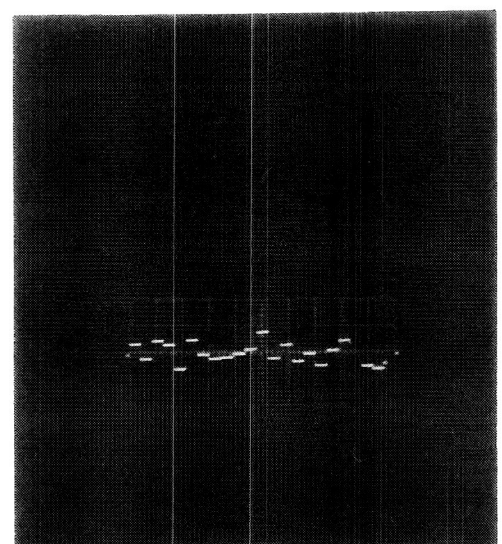
TD-2 (L carrier)
All Channels
Figure 9(c)



L carrier
Channel 7 only
Figure 9(d)



L carrier
All Channels
Figure 9(e)



L carrier
All Channels
Figure 9(f)

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B-12941-2

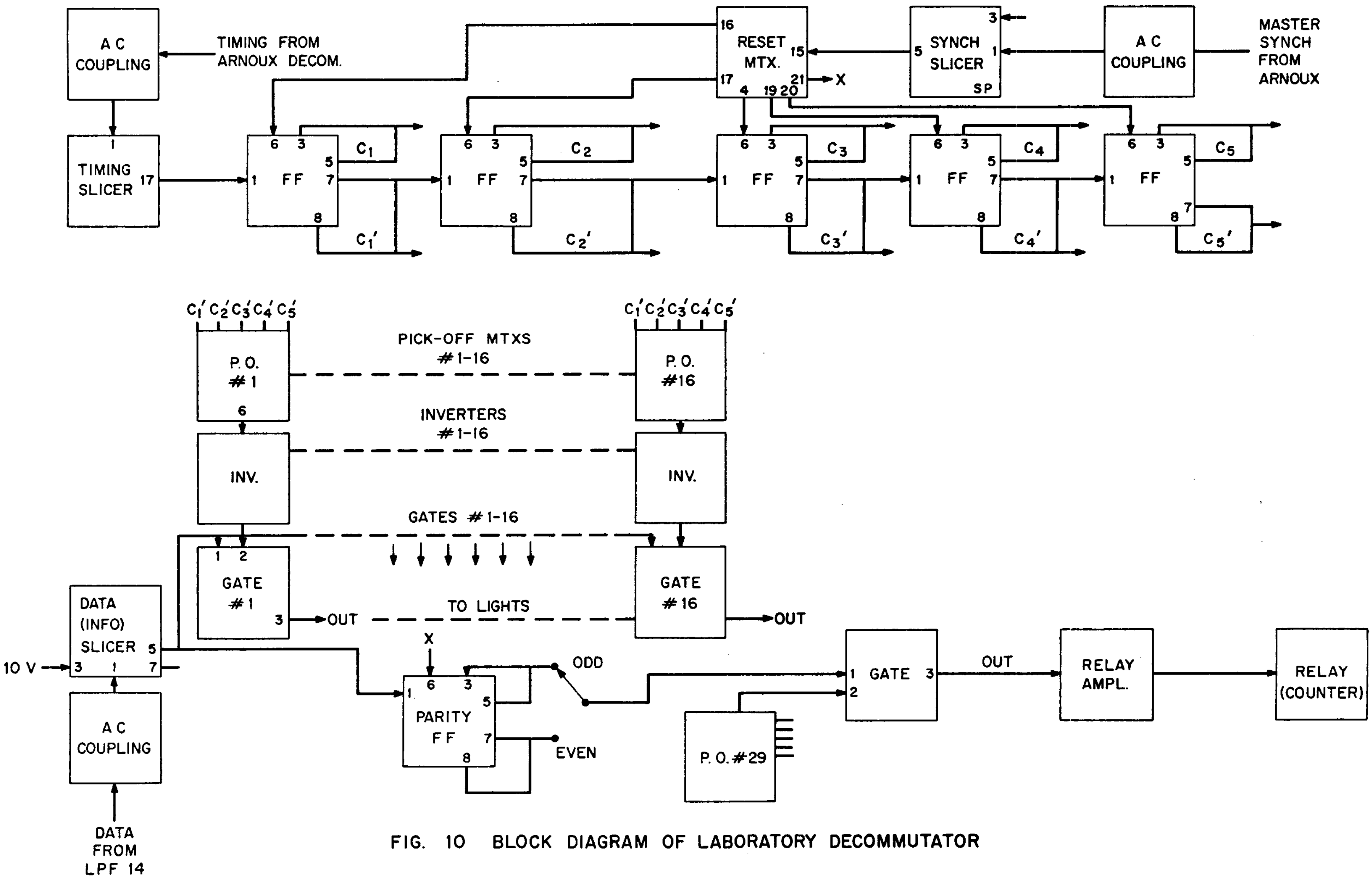
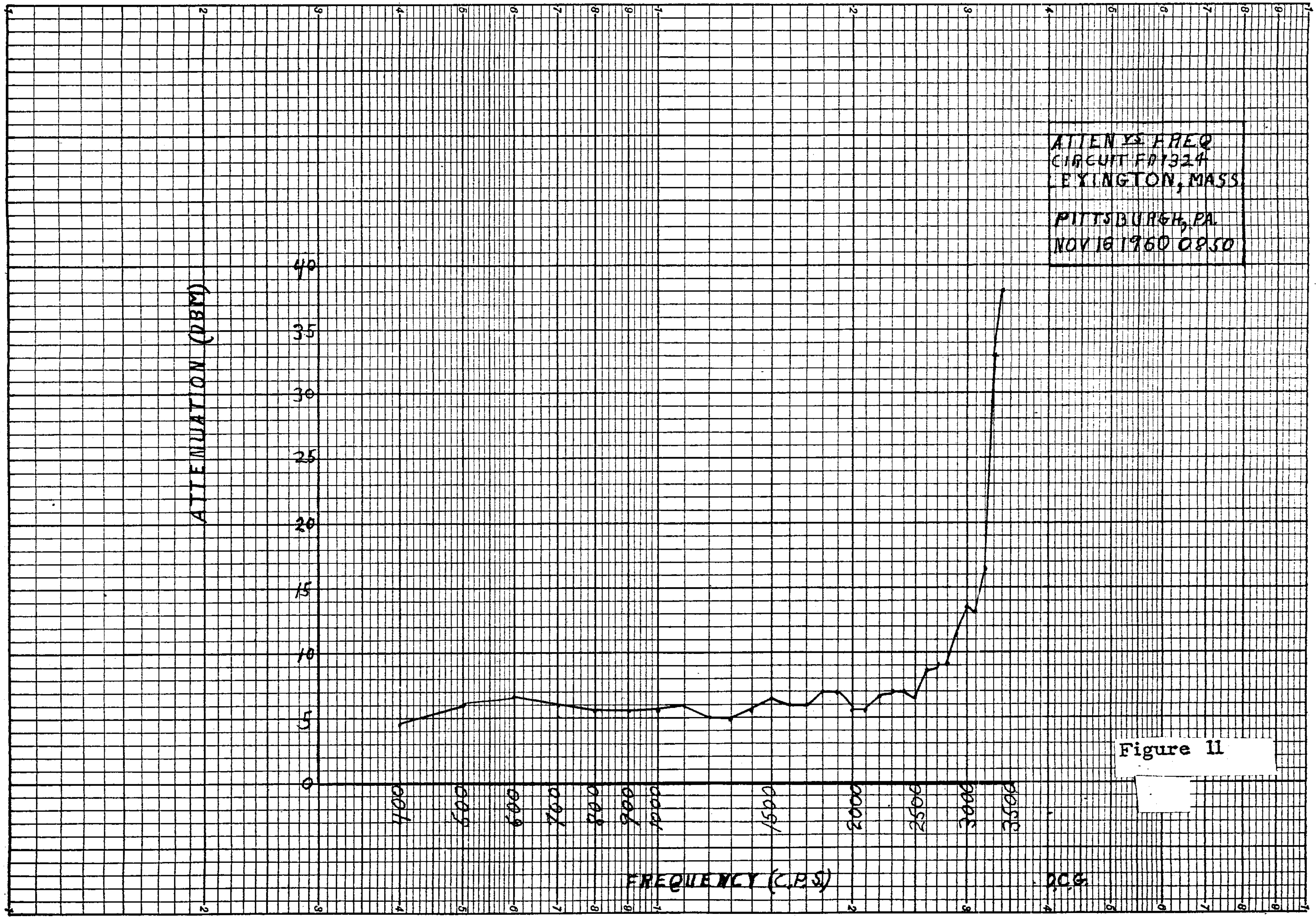
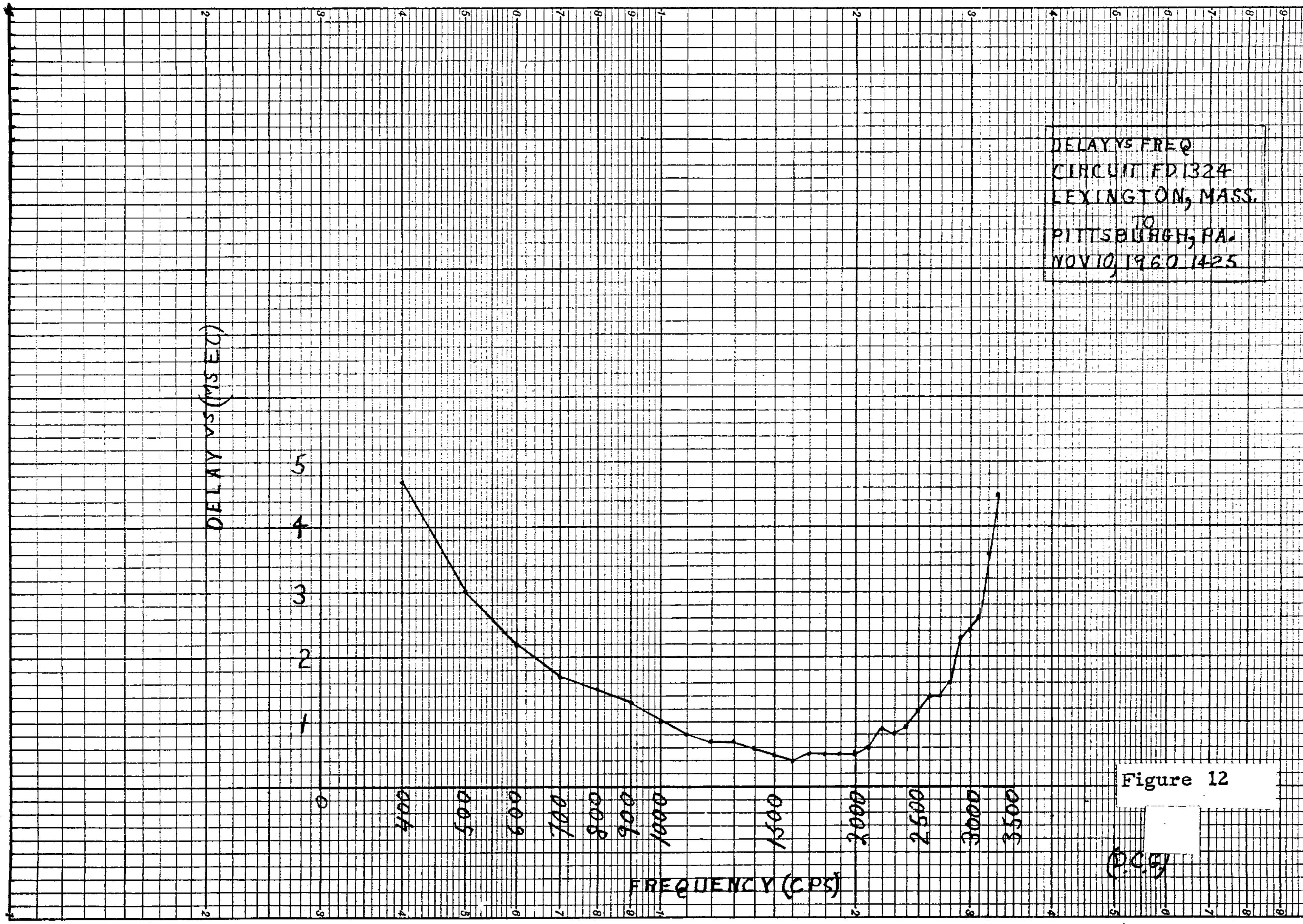


FIG. 10 BLOCK DIAGRAM OF LABORATORY DECOMMUTATOR



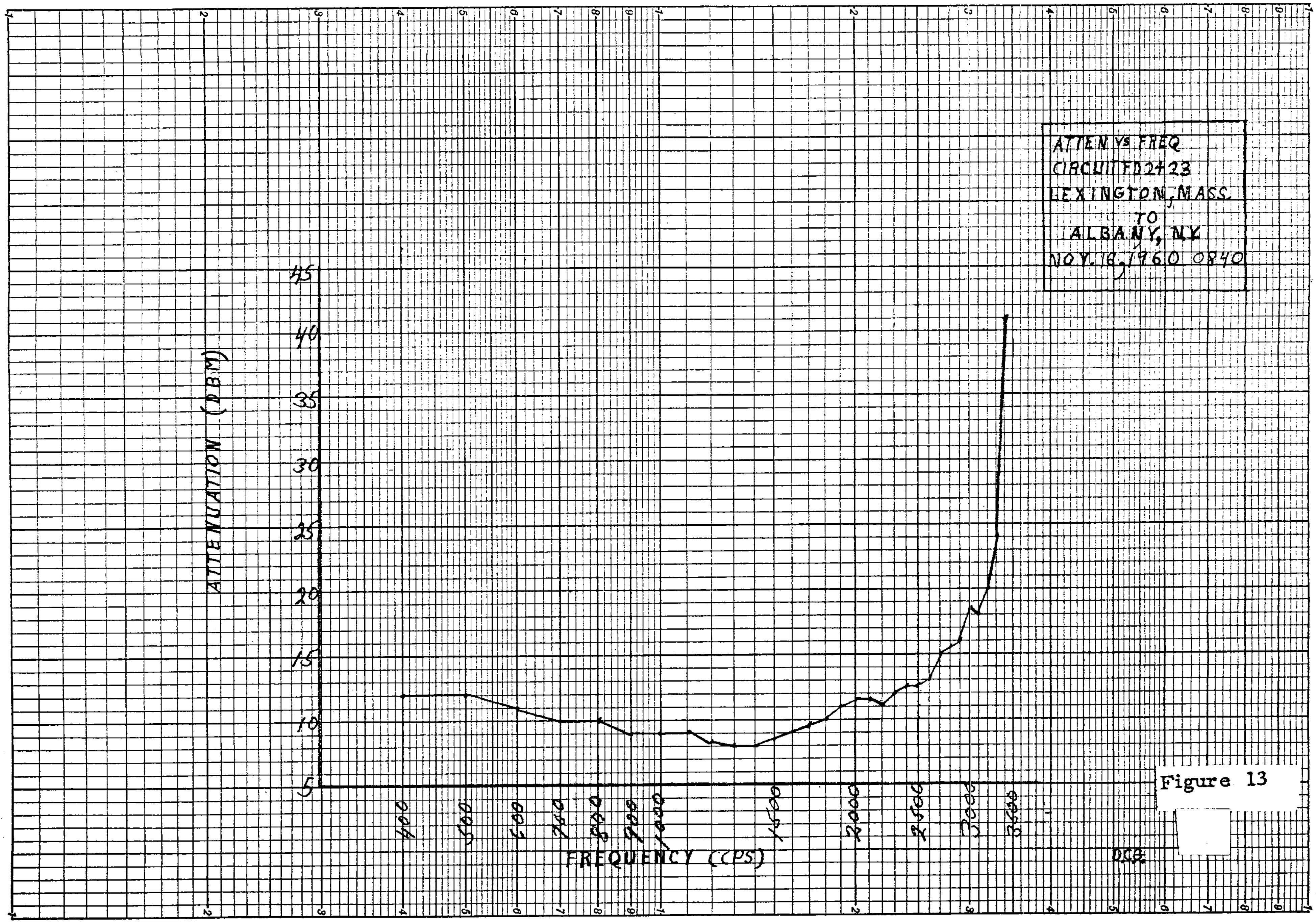
ATTEN VS FREQ
CIRCUIT FA1324
LEXINGTON, MASS
PITTSBURGH, PA
NOV 16 1960 0850
ATTENUATION (DBM)
40
35
30
25
20
15
10
5
0
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCY (C.P.S)
DCG

Figure 11



DELAY VS FREQ
CIRCUIT FD 1324
LEXINGTON, MASS.
TO
PITTSBURGH, PA.
NOV 10, 1960 1425
DELAY VS (MSEC)
5
4
3
2
1
0
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCY (CPS)
(P.C.G.)

Figure 12



ATTEN vs FREQ
CIRCUIT FD2423
LEXINGTON, MASS.
TO
ALBANY, N.Y.
NOV. 16, 1960 0840
ATTENUATION (DBM)
45
40
35
30
25
20
15
10
5
400
500
600
700
800
900
1000
1600
2000
2500
3000
3500
FREQUENCY (CPS)
DCB.

Figure 13

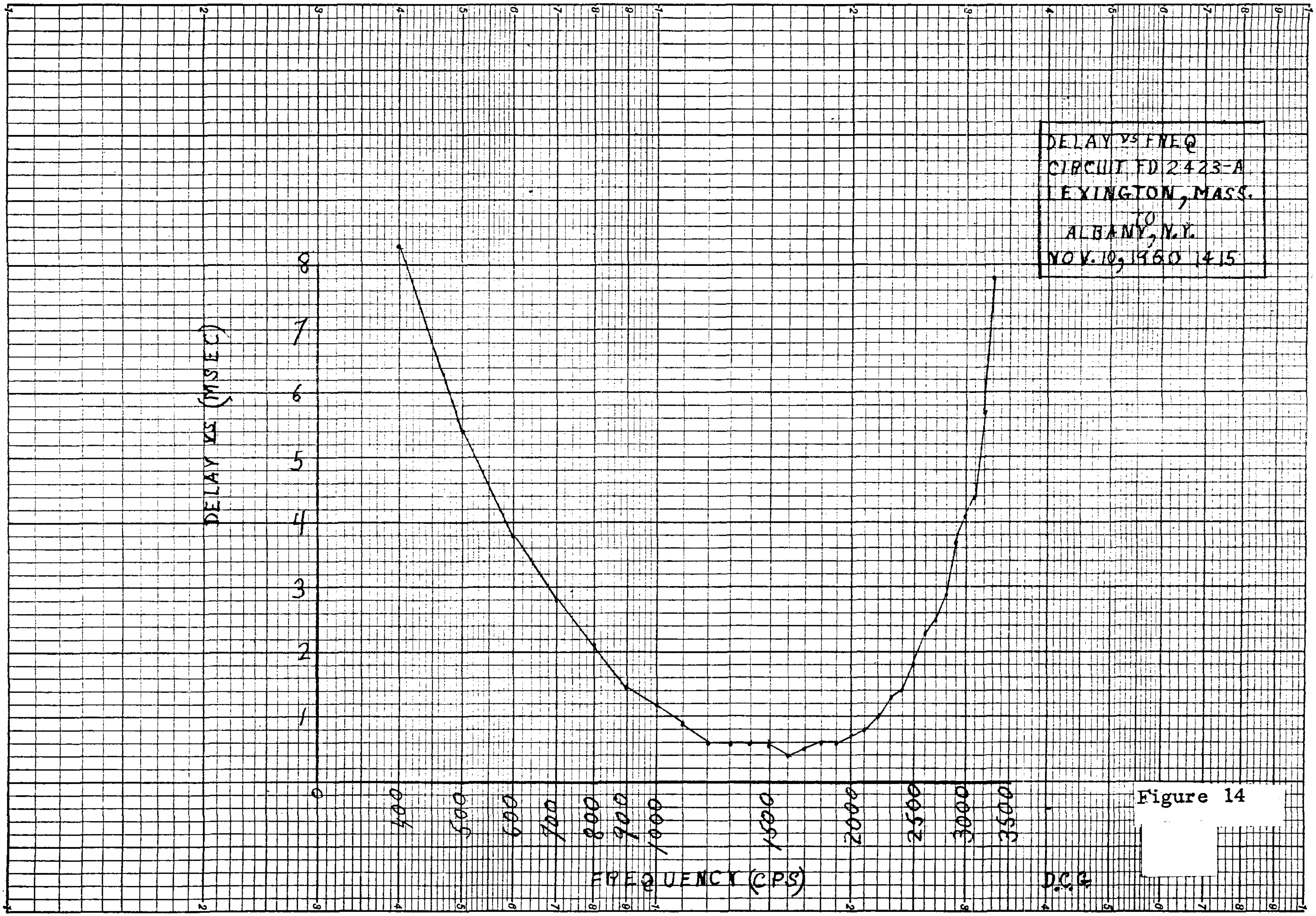
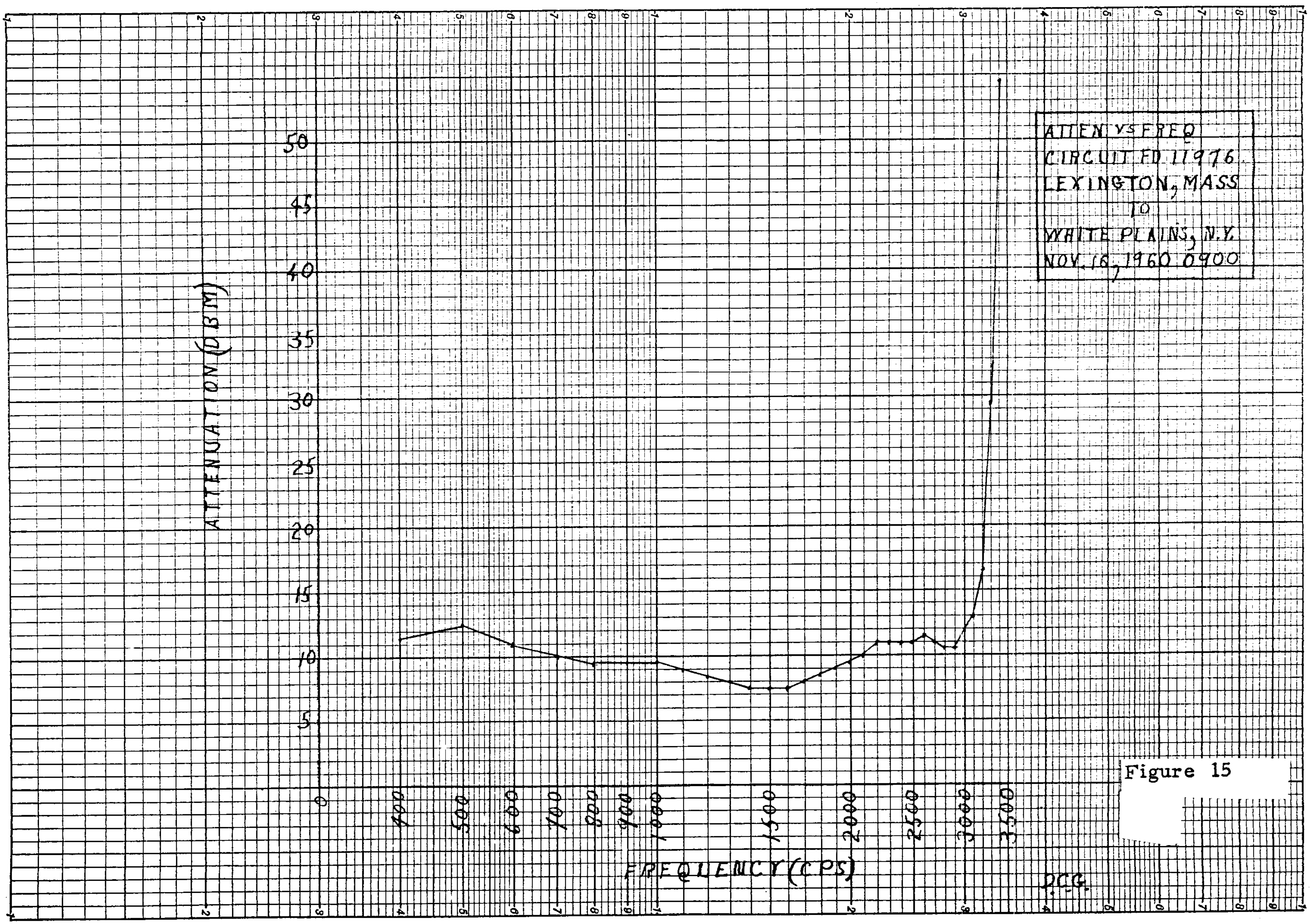

DELAY vs FREQ
CIRCUIT FD 2423-A
LEXINGTON, MASS.
TO
ALBANY, N.Y.
NOV. 10, 1960 1415
DELAY vs (MSEC)
0
1
2
3
4
5
6
7
8
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCY (CPS)
D.C.G.

Figure 14



ATTEN VS FREQ
CIRCUIT FD 11976
LEXINGTON, MASS
TO
WHITE PLAINS, N.Y.
NOV. 16, 1960 0900
ATTENUATION (DBM)
50
45
40
35
30
25
20
15
10
5
0
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCY (CPS)
DCG.

Figure 15

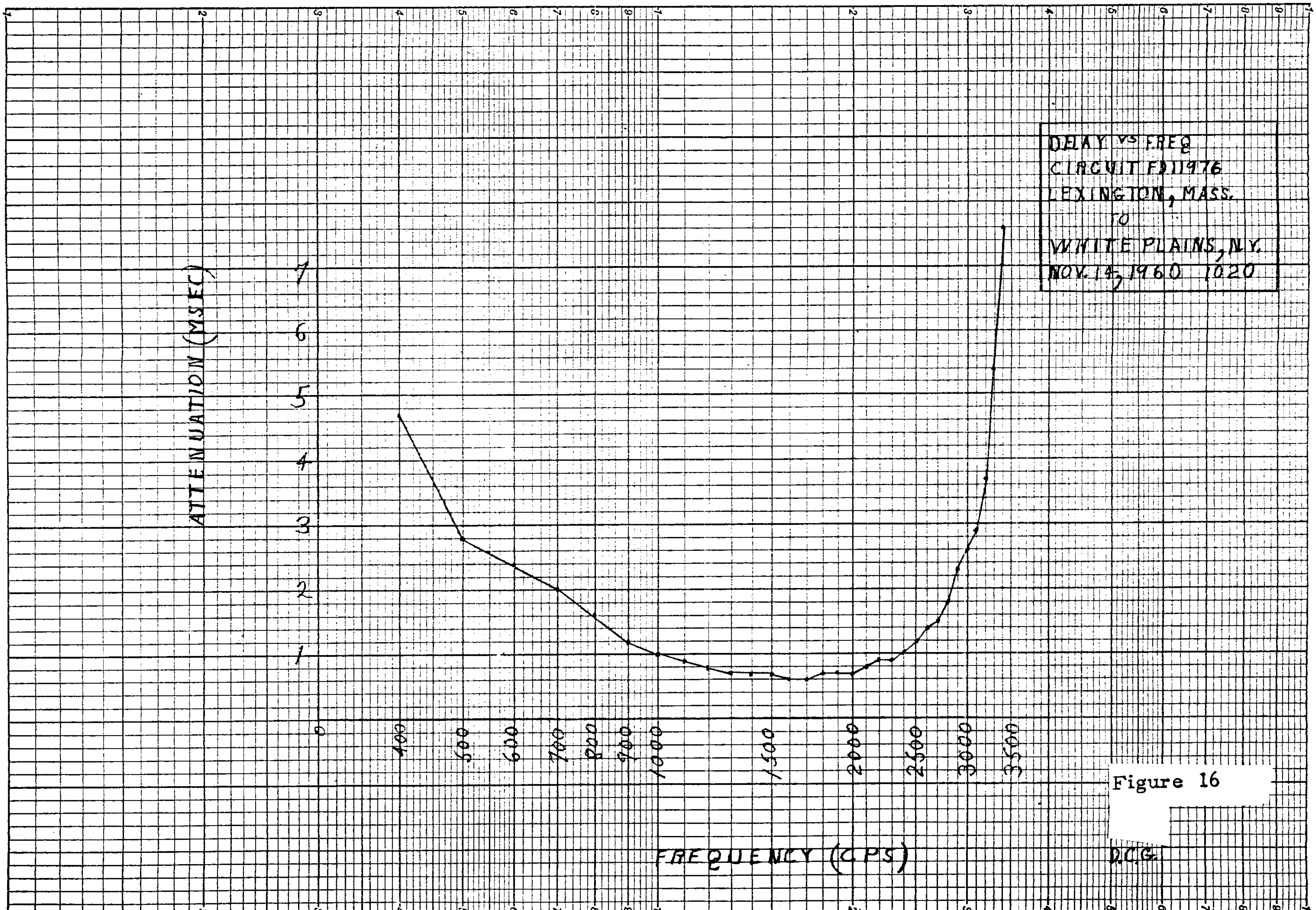
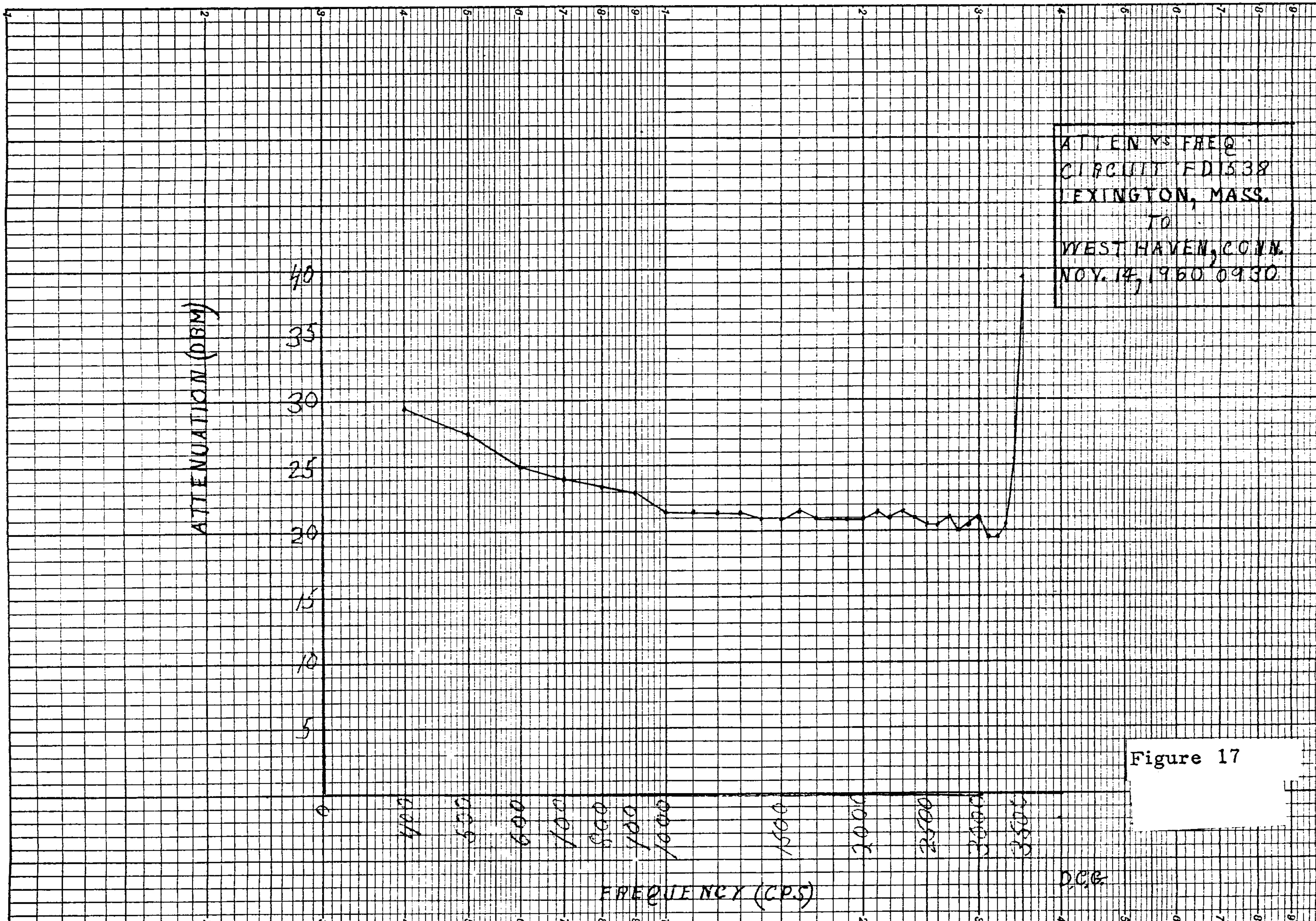

DELAY vs FREQ
CIRCUIT FD11976
LEXINGTON, MASS.
TO
WHITE PLAINS, N.Y.
NOV. 14, 1960 1020
ATTENUATION (MSEC)
1
2
3
4
5
6
7
0
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCY (CPS)
D.C.G.

Figure 16



ATTEN VS FREQ
CIRCUIT FD1538
LEXINGTON, MASS.
TO
WEST HAVEN, CONN.
NOV. 14, 1960 0930
ATTENUATION (DBM)
40
35
30
25
20
15
10
5
0
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCY (CPS)
D.C.G.

Figure 17

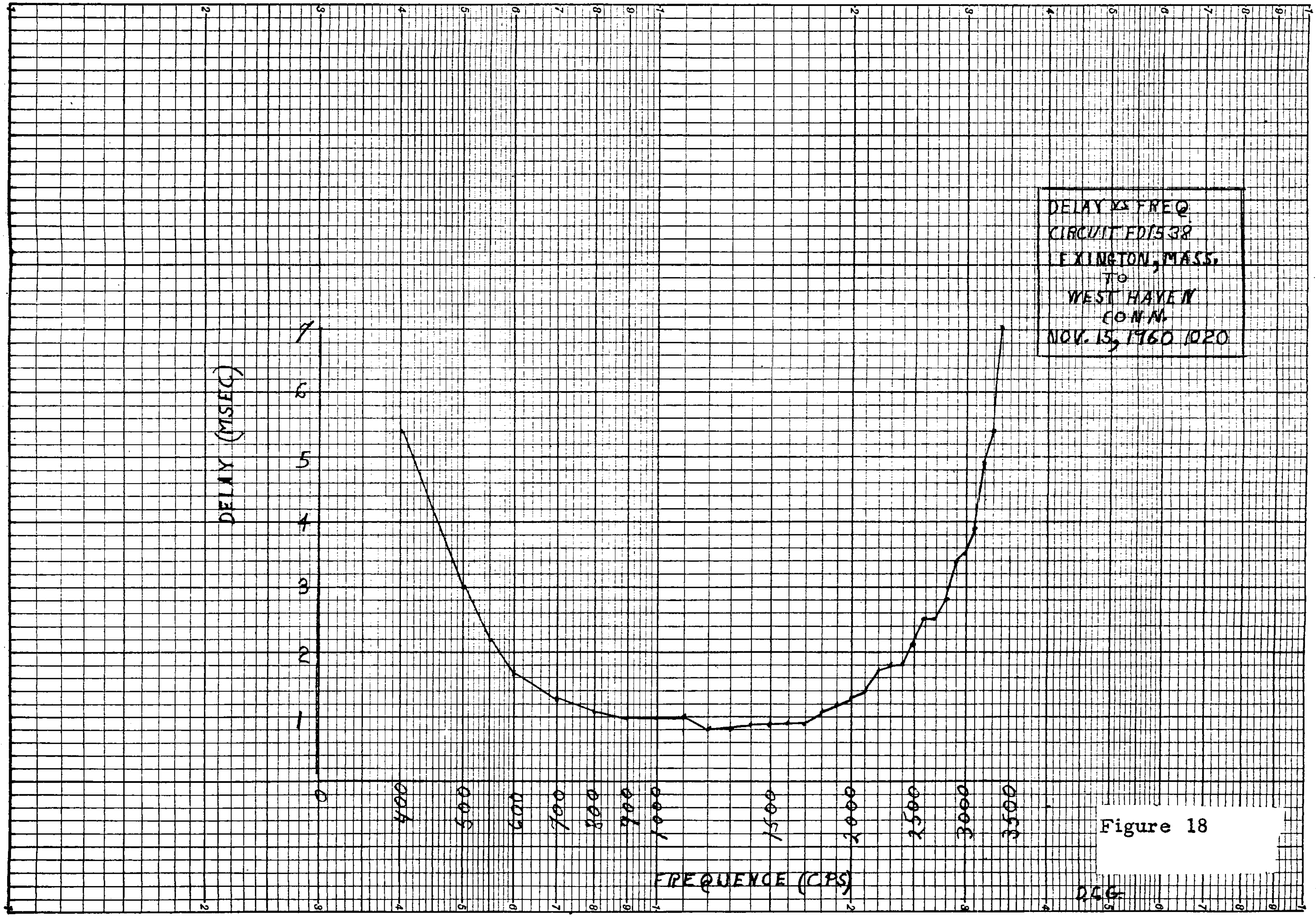

DELAY VS FREQ.
CIRCUIT FD1538
LEXINGTON, MASS.
TO
WEST HAVEN
CONN.
NOV. 15, 1960 1020
DELAY (MSEC)
0
1
2
3
4
5
6
7
400
500
600
700
800
900
1000
1500
2000
2500
3000
3500
FREQUENCE (CPS)
DLG

Figure 18